An *INTEGRAL*/IBIS view of Young Galactic SNRs through the ^{44}Ti gamma-ray lines

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Abstract

We present preliminary results of *INTEGRAL*/IBIS observations on Cas A, Tycho and Vela Junior Supernova remnants in the line emission of ^{44}Ti. This radioactive nucleus is thought to be exclusively produced in supernovae during the first stages of the explosion. It has a lifetime of about 87 y and is then the best indicator of young SNRs, as exemplified by the detection of ^{44}Ti in the youngest known Galactic supernova remnant Cas A with *GRO*/COMPTEL and latter with *BeppoSAX*. In this paper, we will focus on this SNR for which we confirm the detection of ^{44}Ti and point out the importance to know the nature of the hard X-ray continuum, the Tycho SNR, for which no indication of ^{44}Ti was ever reported, and Vela Junior, for which the claimed detection of ^{44}Ti with COMPTEL is still controversial. The *INTEGRAL*/IBIS observations bring new constraints on the nature of these SNRs and on the nucleosynthesis which took place during the explosions.

Key words:
Gamma rays: astronomical observations, Gamma-ray sources (Cas A, Tycho, Vela Junior), Nucleosynthesis in supernovae, Supernova remnants in Milky Way
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1 Introduction

Supernovae (hereafter SNe) are the main galactic nucleosynthesis sites of production of radioisotopes which may be observed through their γ-ray line emission. Some of them are short-lived such as ^{44}Ti. The radioactive decay chain ^{44}Ti$\longrightarrow^{44}$Sc$\longrightarrow^{44}$Ca, with a half-life of about 60 yrs (Wietfeldt et al., 1999), produces three lines at 67.9 keV, 78.4 keV (from ^{44}Sc*) and 1157 keV (from ^{44}Ca*) with similar branching ratios. This radioactive nucleus is thought to be created in all types of SNe but with a large variation of yields per type: from a few 10^{-5} to $\sim 2 \times 10^{-4}$ $M_{\odot}$ for the most frequent SNe of Type II (Woosley & Weaver, 1995; Thielemann et al., 1996) and Type $I_{b/c}$ (Woosley et al., 1995) and up to 3.9×10^{-3} $M_{\odot}$ for the rare event of the He-detonation of a sub-Chandrasekhar white dwarf (Woosley, Taam & Weaver, 1986; Woosley & Weaver, 1994). As reported by Iwamoto et al. (1999), the ^{44}Ti yields for standard Type Ia SNe are between 8×10^{-6} $M_{\odot}$ and 5×10^{-5} $M_{\odot}$. It is primarily generated in the α-rich freeze-out from nuclear statistical equilibrium occurring in the explosive silicon burning stage of core-collapse SNe, while a normal freeze-out Si burning is at play in Type Ia SNe (Thielemann, Nomoto & Yokoi, 1986). Therefore, it probes deep into the interior of these exploded stars and provides a direct way to study the SN-explosion mechanism itself. On the other hand, it is strongly dependent on the explosion details, mainly on the mass-cut in core-collapse SNe (the mass above which matter is ejected), the energy of the explosion and asymmetries.

The *INTEGRAL* observatory (Winkler et al., 2003) carries two main instruments: IBIS (Ubertini et al., 2003) and SPI (Vedrenne et al., 2003). Both can provide images and spectra, based on the coded mask aperture system, working from 15 keV to 1 MeV and from 20 keV to 8 MeV, respectively. The line-sensitivity of the IBIS low-energy camera ISGRI (Lebrun et al., 2003) is really appropriate to detect the two low energy ^{44}Ti γ-ray lines at 67.9 and 78.4 keV (ΔE $\sim$ 6 keV FWHM at 70 keV). With a spectral resolution of $\sim$ 2 keV at 1 MeV, SPI can measure the ejecta velocity due to the Doppler broadening. We present here preliminary results on three young SNRs: Cas A, Tycho and RX J0852-4622 (Vela Jr).

2 The Cassiopeia region: Cas A and Tycho SNRs

The Cassiopeia region was observed by *INTEGRAL* for a duration of $\sim$ 1.5 Ms. Figure 1 shows the region as observed by IBIS/ISGRI in the 25-40 keV band. Several sources have been revealed, amongst them Cas A detected at $\sim 25\sigma$ confidence level and Tycho SNR detected at $\sim 6\sigma$ confidence level.

The discovery of the 1157 keV ^{44}Ti γ-ray line emission from the youngest Galactic SNR Cas A with COMPTEL (Iyudin et al., 1994) was the first direct proof that

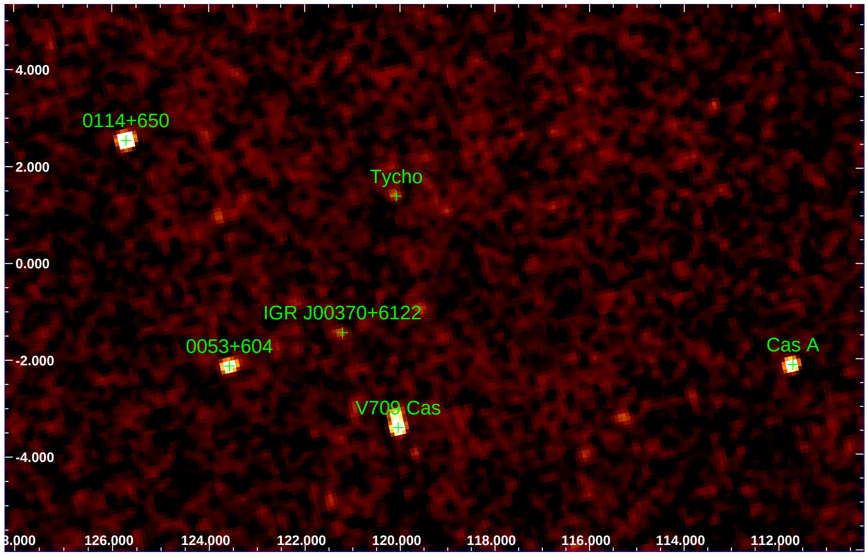

Fig. 1. A IBIS/ISGRI image of the Cassiopeia region in the 25-40 keV energy band. Cas A and Tycho are detected at ~ 25σ and 6σ, respectively.

this isotope is indeed produced in SNe. This has been strengthened by the *BeppoSAX*/PDS detection of the two low-energy ^{44}Ti lines (Vink et al., 2001). By combining both observations, Vink et al. (2001) have deduced a ^{44}Ti yield of (1.5±1.0) $\times\ 10^{-4}$ $M_\odot$. This huge value compared to those predicted by most of the models could be due to several effects: a large energy of the explosion (~ 2×10^{51} erg), asymmetries (Nagataki et al., 1998) currently observed in the ejecta expansion, and a strong mass loss of the progenitor consistent with the scenario of a Type Ib SN (Vink, 2004). In the case of Cas A, the knowledge of the continuum emission is critical to properly measure the ^{44}Ti line flux. Unfortunately, it is still debated whether the nonthermal hard X-ray continuum is synchrotron radiation or nonthermal bremsstralhung from supra-thermal electrons (see Vink 2005 for a recent review and references therein).

Figure 2 presents the spectrum obtained with IBIS/ISGRI (in black, Vink 2005) compared to that of BeppoSAX/PDS (in grey). There is a 3σ excess at the position of the first ^{44}Ti line with respect to a power-law continuum emission $\Gamma \sim 3.3$ (solid line). Both spectra are compatible, however, since there is still no clear detection of the continuum beyond the two ^{44}Ti lines, the weak S/N of the second line could be due to a steepening above ~ 60 keV, predicted for all synchrotron and some bremsstrahlung models. Assuming a power-law spectrum, the flux of the first ^{44}Ti line and that of each line by fitting both jointly are $(2.3 \pm 0.8) \times 10^{-5}$ cm^{-2} s^{-1} and $(1.2 \pm 0.6) \times 10^{-5}$ cm^{-2} s^{-1}, respectively. By analyzing the SPI data, we didn't find any excess neither in the broad (1142 - 1172 keV) nor in the narrow energy band around the 1.157 MeV ^{44}Ti line yielding to a preliminary 2σ lower limit on the ejecta velocity $\Delta v > 10^3$ km s^{-1} for an assumed line flux of 1.9×10^{-5} cm^{-2} s^{-1}.

The Tycho SNR is the prototype of a Type Ia SN (Baade, 1945). No evidence of ^{44}Ti

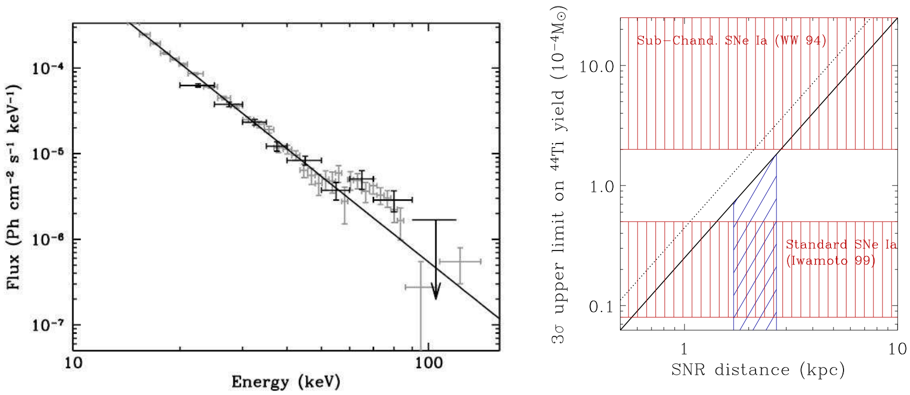

Fig. 2. (left) Spectrum of Cas A obtained with IBIS/ISGRI (in black) compared to that of *BeppoSAX*/PDS instrument (in grey). The continuum is assumed to be a single power-law with a spectral index of ~ 3.3. (right) 3σ upper limit on the ^{44}Ti yield in Tycho as a function of the distance (black solid line). The dotted line corresponds to the *GRO*/COMPTEL results after the first 3 years (Dupraz et al., 1997). The two red areas represent the calculated yields for "standard" and Sub-Chandrasekhar He-detonation Type Ia SNe.

has ever been reported (Dupraz et al., 1997). With an age of 433 yr and a distance of 2.2 ± 0.5 kpc, this SNR is the most promising candidate to observe explosive nucleosynthesis products of thermonuclear SNe. As shown in Figure 1, this SNR is detected by ISGRI in the hard X-ray continuum up to ~ 50 keV but we didn't find any significant excess in the range of the two low energy ^{44}Ti lines. Our 3σ upper limit of 1.5×10^{-5} cm^{-2} s^{-1} can be translated into an upper limit on the ^{44}Ti yield. Figure 2 shows this value as a function of the distance of the SNR. One can see that all the models of Sub-Chandrasekhar Type Ia SNe, predicting huge ^{44}Ti yields, are excluded for any distance inside the uncertainties. On the other hand, we cannot at this time really constrain the "standard" Type Ia models exposed by Iwamoto et al. (1999). Further results on these two SNRs based on a significantly longer observing time (~ 3 Ms) are expected in the near future.

3 Vela Junior

Since its detection with *ROSAT* and COMPTEL in the Vela region, RX J0852-4622 (Vela Jr) is still a mystery. Previous estimates based on its apparent diameter (~ 2°), the spatially coincident excess in the 1.157 MeV ^{44}Ti line, and the *ROSAT* X-ray spectrum have showed that this SNR is likely young (~ 700 yr) and nearby (~ 250 pc). However, the relative strong absorption observed by *ASCA* towards the source and the weak radio flux support a "not so nearby, and so, not so young" scenario. Moreover, the re-analysis of the COMPTEL data found that the detection of this SNR as a ^{44}Ti source is only significant at the 2-4σ confidence level. Surprisingly, Tsunemi et al. (2001) and Iyudin et al. (2005) have detected a feature in the X-ray spectrum at ~ 4.1 keV which could come from Ti and Sc excited by high velocity

collisions in the SNR outer shell. Iyudin et al. (2005) argued that the consistency of this X-ray line flux and the 1.15 MeV ^{44}Ti line flux seems to support the first estimations of age and distance. *INTEGRAL* has deeply observed this region during the two first years. We have analyzed data in the range of the two low energy ^{44}Ti lines but we did not find any evidence of ^{44}Ti. Our non-detection could be compatible with the COMPTEL findings if Vela Jr appears as an extended source for the IBIS telescope: in that case, the total flux should be diluted over all the sky pixels and then in any direction within the remnant, the flux would go below our sensitivity. Our 3σ upper limit is close to one fourth of the COMPTEL flux and then we can exclude four separated point-like sources (Φ < 8') with the same flux inside the remnant (*i.e.* a scenario where the ^{44}Ti would be located in "hot-spots"). A method to reconstruct the flux of an extended source with a coded mask telescope is under study (Renaud et al., 2006).

SNR	ISGRI	SPI
Cas A	$2.3^{\pm 0.8} \times 10^{-5}$ cm^{-2} s^{-1} (67.9 keV)	$< 3.1 \times 10^{-5}$ cm^{-2} s^{-1}
Tycho	$< 1.5 \times 10^{-5}$ cm^{-2} s^{-1} (67.9 & 78.4 keV)	?
Vela Jr.	$< 10^{-5}$ cm^{-2} s^{-1} (67.9 & 78.4 keV)	$< 1.1 \times 10^{-4}$ cm^{-2} s^{-1} (78.4 keV)

Table 1
Summary of the preliminary results obtained with *INTEGRAL* in the range of the ^{44}Ti γ-ray lines. The upper limits were calculated assuming that sources appear as point-like and are given at the 3σ confidence level.

4 Discussion

This paper summarized our preliminary results on young SNRs through the ^{44}Ti γ-ray lines. One of the main goal within this framework is the search for "young, missing, probably hidden" SNRs. The non-detection by HEAO-3, SMM and recently COMPTEL of any such sources in the inner part of the Galaxy seems to be incompatible with what we expect to see from 3 SNe per century, most of them core-collapse SNe, producing $\sim 10^{-4}$ $M_{\odot}$ of ^{44}Ti, as observed in Cas A or derived for SN 1987A. On the other hand, current nucleosynthesis models can only explain one third of the solar abundance of ^{44}Ca (Timmes et al., 1996), thought to come mainly from the radioactive decay chain of the ^{44}Ti. We also performed a first analysis of the Galactic Central regions with IBIS/ISGRI and confirm that there is no evidence of any strong excess, *i.e.* a young SNR (Renaud et al., 2004). In any case, these first results show that we can study γ-ray lines with the IBIS/ISGRI with a line sensitivity after only two years of observation better than those of previous γ-ray instruments and then bring new constraints on the explosive nucleosynthesis production in SNe.

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